AD

Research and Development Technical Report
ECOM-0268-5

AD 748090

ELECTRON BOMBARDED SEMICONDUCTOR

SHORT PULSE GENERATOR

FIFTH TRIANNUAL REPORT

1 December 1971 through 31 March 1972

CONTRACT No. DAAB07-70-C-0268

W-J Project No. 22-4083

Prepared by

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September 1972

SEE AD 741856

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1. ORIGINATING ACTIVITY (Corporate author) Watkins-Johnson Company 3333 Hillview Avenue Palo Alto, California 94304	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

Electron Bombarded Semiconductor Short Pulse Generator

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

Tri-Annual 1 December 1971 to 31 March 1972.

5. AUTHOR(S) (First name, middle initial, last name)

Aris (nmi) Silzars

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
September 1972	22	0

8a. CONTRACT OR GRANT NO. DAAB07-70-C-0268 b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) 22-4083-5 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) ECOM 0268-5

10. DISTRIBUTION STATEMENT

Approved for public release, distribution unlimited.

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	U. S. Army Electronics Fort Monmouth, N. J. 07703 AMSEL-TL-BS

13. ABSTRACT

Improved fabrication processes for large area semiconductor targets and complete high current amplifiers were developed. Large area (1.40 sq. cm. active area) semiconductor diodes, with leakage current of less than 10 mA at reverse bias voltages of 250 volts were fabricated. Initial tests were made on a completely processed tube with an internal getter instead of a two liter appendage pump. Three complete high current pulse amplifiers were fabricated and tested for diode saturation characteristics and pulse performance . The performance was determined for both grid-driven and cathode-driven operation.

DD FORM 1 NOV 65 1473

Unclassified
Security Classification

14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Electron Beam						
Electron Bombarded						
Semiconductor						
Pulse Amplifier						
Pulse Generator						
High-Current Switch						
Short Pulse Generator						
Gridded Gun						
Silicon						
Diode						
PN Junction						

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FIFTH TRIANNUAL REPORT

1.0 INTRODUCTION

The objective of this program is to conduct an investigation leading to the development of a high-speed high-current pulsed amplifie.. The performance goals of this high current EBS switch are 400 amperes of output current into an 0.5 ohm load with less than 1 nanosecond risetime.

The objective during this fifth reporting period has been to refine the semiconductor fabrication technology and device fabrication techniques.

The objective during the next triannual reporting period will be to complete assembly of four additional high current pulse amplifiers with improved large area semiconductor targets and optimized grid-cathode structures.

The high-current switch for this program utilizes a planar triode electron source bombarding a reversed biased semiconductor diode target. The device must be simple, reliable, and inexpensive.

2.0 PROGRAM SUMMARY

2.1 Summary of Work

The program during this fifth triannual period emphasized the refinement of semiconductor targets in preparation for fabrication of engineering prototype high current pulse amplifiers.

Improvements in semiconductor fabrication techniques produced new diodes of .35 cm^2 area and 1.40 cm^2 area with lower leakage currents and higher breakdown voltages than previously available. Fabrication yield and consistency of electrical parameters was improved by the use of a guard-ring structure and by tighter specification on the silicon material. In a joint effort with the other funded and internally supported EBS programs a new radiation resistant integral beam shield structure was developed. Tests in a scanning electron microscope showed more than an order of magnitude improvement in leakage current stability compared to similar diodes without an integral beam shield.

Improvements were also made in the tube fabrication techniques. The grid to grid ring braze was further improved.

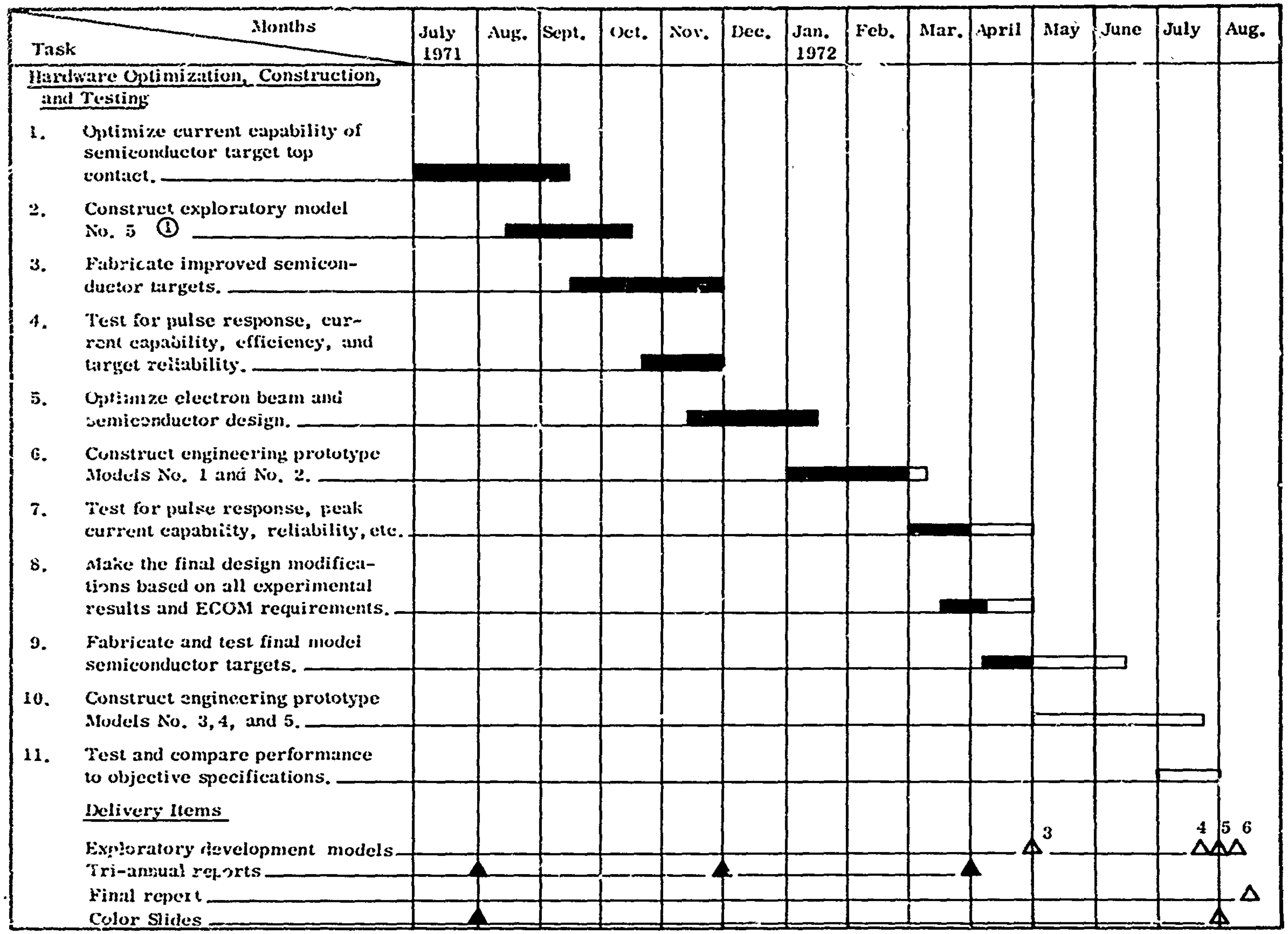
Three complete pulse amplifiers were fabricated and tested during this reporting period. One of these tubes was operated with an internal getter and no appendage pump.

Detailed pulse tests on three tubes investigated diode saturation characteristics and the beam current pulse at various beam potentials and drive levels. Several different input and output coupling circuits were tested to improve peak current capability and output pulse shape. The tubes were operated with the pulse applied to the grid and alternately to the cathode. The information obtained from these experiments will be used to optimize the design of the engineering prototype devices.

2.2 Program Schedule

Table I shows the Program Plan for July 1971 through August 1972. The program plan is presented in bar chart form and the solid bars indicate our estimate of completed work. As can be seen from Table I, the program effort and time schedule are approximately as planned, although the work is proceeding more in parallel than was originally estimated.

During the next triannual reporting period we expect to complete all of the tasks listed and to deliver four additional EBS pulse amplifiers to ECOM Evans Laboratory. At the present time we are making final tests on a triode to measure electron beam and modulating structure characteristics. The final evaluation of the semiconductor target design is also under way. The results of these evaluations will be incorporated into the design of the engineering prototype models.



1 Four models have been constructed during the first year of the program.

Table I - Program Plan for July 1971 to August 1972

3.0 SEMICONDUCTOR TARGET FABRICATION

The high current pulse amplifier requires a 140 mm^2 semiconductor diode to achieve the 400 amperes of current with 1 nanosecond risetime. Because of this very large target area and the unique requirements of the EBS amplifier configuration it was not certain at the beginning of this program whether such a target could be economically fabricated as a single diode. In the first and second triannual reports we discussed some of the anticipated problems with particular emphasis on fabrication yield, top contact metallization, and interconnection of targets to the output structure. During the third and fourth triannual period we successfully fabricated large area targets with the design goal resistivity and depletion region thickness.

During this reporting period the emphasis has been on fabrication techniques to improve yield, reduce diode leakage current, improve voltage breakdown characteristics, and to develop an integral beam shield.

3.1 Fabrication of Large Area Targets

New fabrication runs of large area diodes (1.40 cm^2 and .35 cm^2) have been completed. Several of the 1.4 cm^2 diodes were found with leakages less than 10 mA at 250 volts, and a significant number of 0.35 cm^2 diodes with leakages less than 5 mA at 250 volts. Targets have been fabricated from these diodes. Figures 3.1 and 3.2 show photographs of two complete target assemblies, one with the full size 1.40 cm^2 target and the other with four quarter-section (.35 cm^2) diodes. These targets will be assembled into the next complete pulse amplifiers and tested under electron beam bombardment. The reverse bias characteristics of the full size (1.40 cm^2) diode are shown in Figure 3.3.

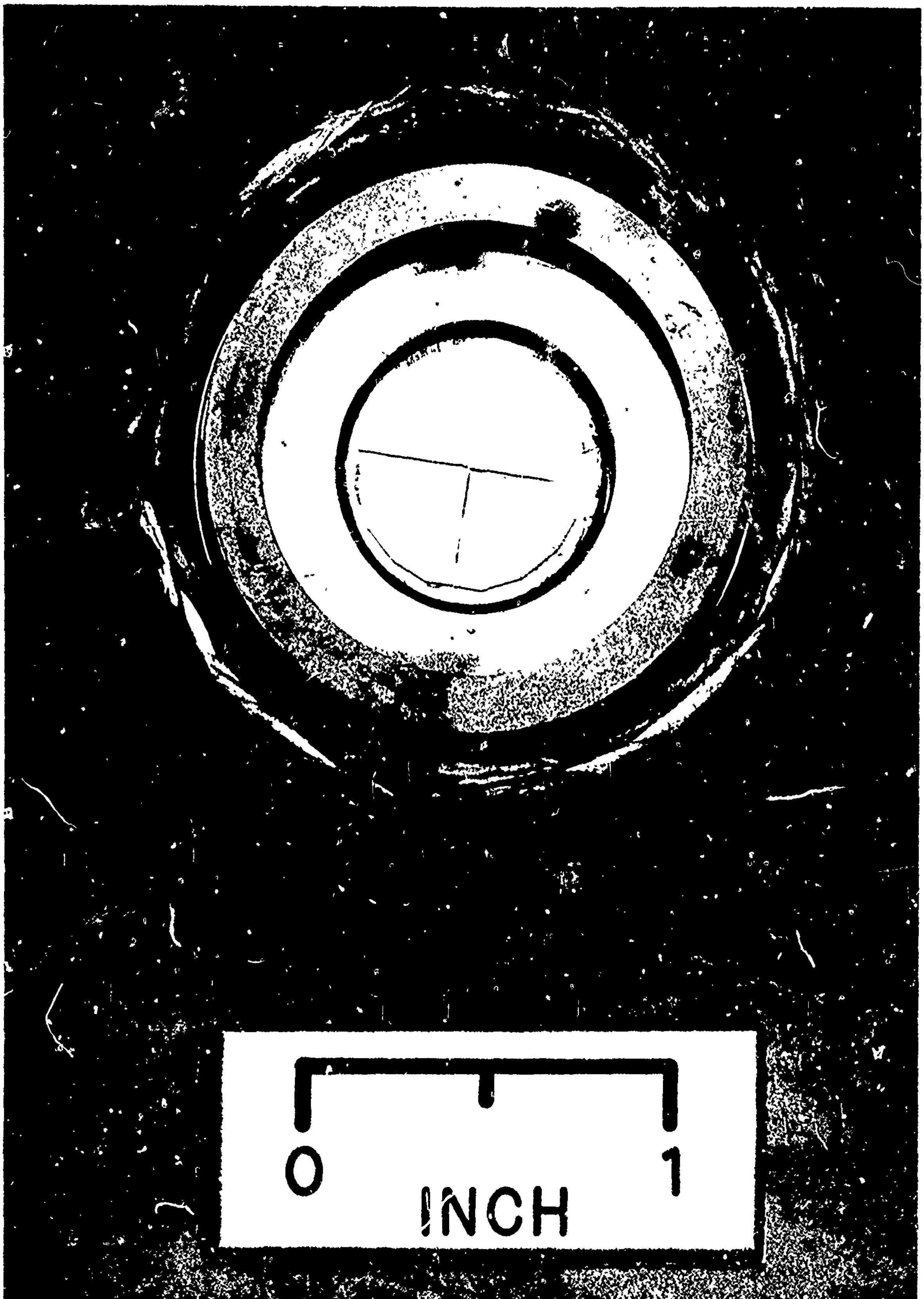


Fig. 3.1 - Completed target assemoly with four quarter section diodes.

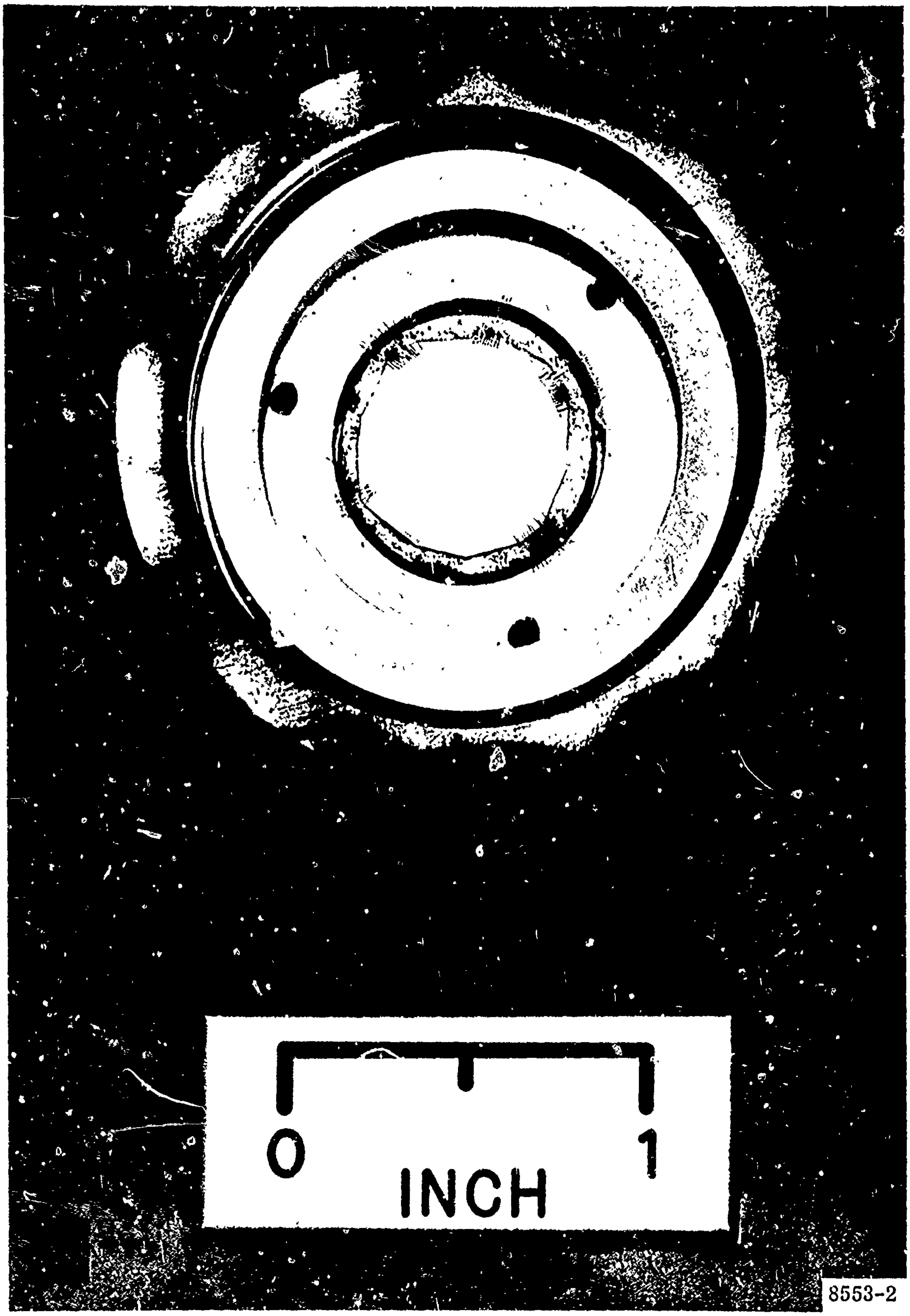


Fig. 3.2 - Completed target assembly with a full size 1.40 cm^2 target.

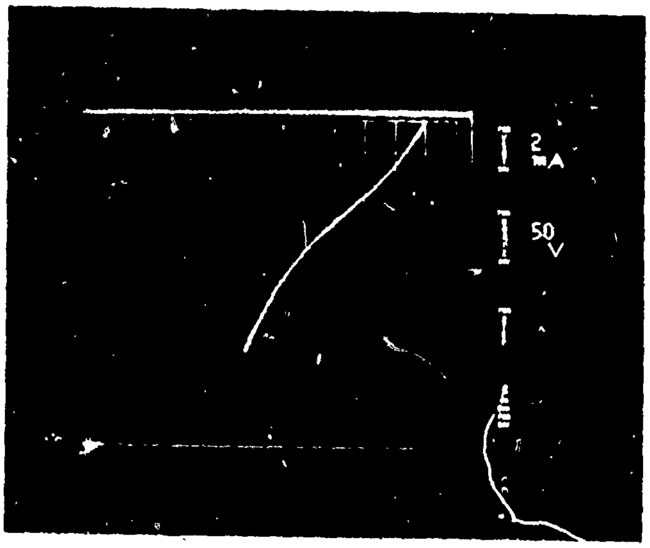


Fig. 3.3 - Reverse bias characteristics of a full size (1.40 cm^2) diode. The origin is at the upper right corner.

At the present time there are two major sources of yield loss in fabricating these diodes:

1. Bulk defects that lie either across the junction or in the depletion region and have large generation/recombination currents,
2. Surface defects that either have a high surface recombination velocity or that "pin" the surface potential and prevent the depletion region from spreading at the surface of the silicon.

Bulk defects that are electrically active are basically controlled by the perfection of the material. We are fabricating diodes from Czozhralski grown material and from material which has been float/zoned to remove carbon, oxygen, and nitrogen. Because of the very large target area which permits only about 20 diodes/wafer, our statistics are not yet adequate to reveal a significant difference in yield due to the starting material.

Surface imperfections are generally introduced during processing. Improper cleaning, dust particles, and oxide pinholes are common imperfections. Work has continued to refine the processing to minimize surface contamination since investigation on a related project of yield on 2.5 mm^2 diodes indicated that surface problems were a major cause of low yields for those diodes.

3.2 Semiconductor Target Reliability Study

Our tests to date have not shown significant degradation of large area targets during operation in the high current pulse amplifiers. However, these tests have been of limited duration and it is possible that further testing will reveal long term degradation effects. This degradation could be due to either electron radiation damage or failure of the metal interconnect. The most pronounced mode of failure due to radiation of diodes made on n-type silicon is that the electron radiation penetrates to the oxide silicon interface and produces fixed positive

charge. The fixed charge causes electron in the silicon to accumulate near the surface, preventing the diode depletion region from spreading and causing premature breakdown at the surface. An important feature of the diode design has been to provide sufficient shielding to prevent the radiation from penetrating to the interface. Recently we have completed development of a radiation resistant design using an integral beam shield.

The possible diode failure due to the occurence of voids in metal caused by electromigration after an extensive period of operation has not been observed in the high current switch. As discussed in the second triannual report, a process is used to slope the edges of the dielectrics. This avoids steep steps in the aluminum overlayer which helps to minimize the formation of microcracks. These microcracks are nucleating sources of electromigration. To our knowledge, noone has reported the electromigration properties of metal systems carrying large pulses of current for short periods. We routinely monitor the metallization of diodes that have been subjected to beam bombardment for changes which might indicate that electromigration will lead to failure of the metallization system.

3.3 Radiation Resistant Design Using an Integral Beam Shield

A new technique for shielding the semiconductor-oxide interface has been developed in a joint effort on all of our funded and IR&D EBS programs. This technique utilizes a metal beam lead frame structure which completely shields the junction from electron beam bombardment. A schematic of the radiation hardened diode using this pillar beam mask to completely shield the oxide and p-glass around the junction periphery is shown in Fig. 3.4. A photograph of diodes fabricated using this technique is shown in Fig. 3.5.

Diodes with 1 x 2.5 mm active area and with the integral beam mask have been recently tested in the scanning electron microscope and the results compared to a similar diode without the integral beam mask. The beam was swept over the entire diode surface, past the metallization and onto the phosphorous glass region of the

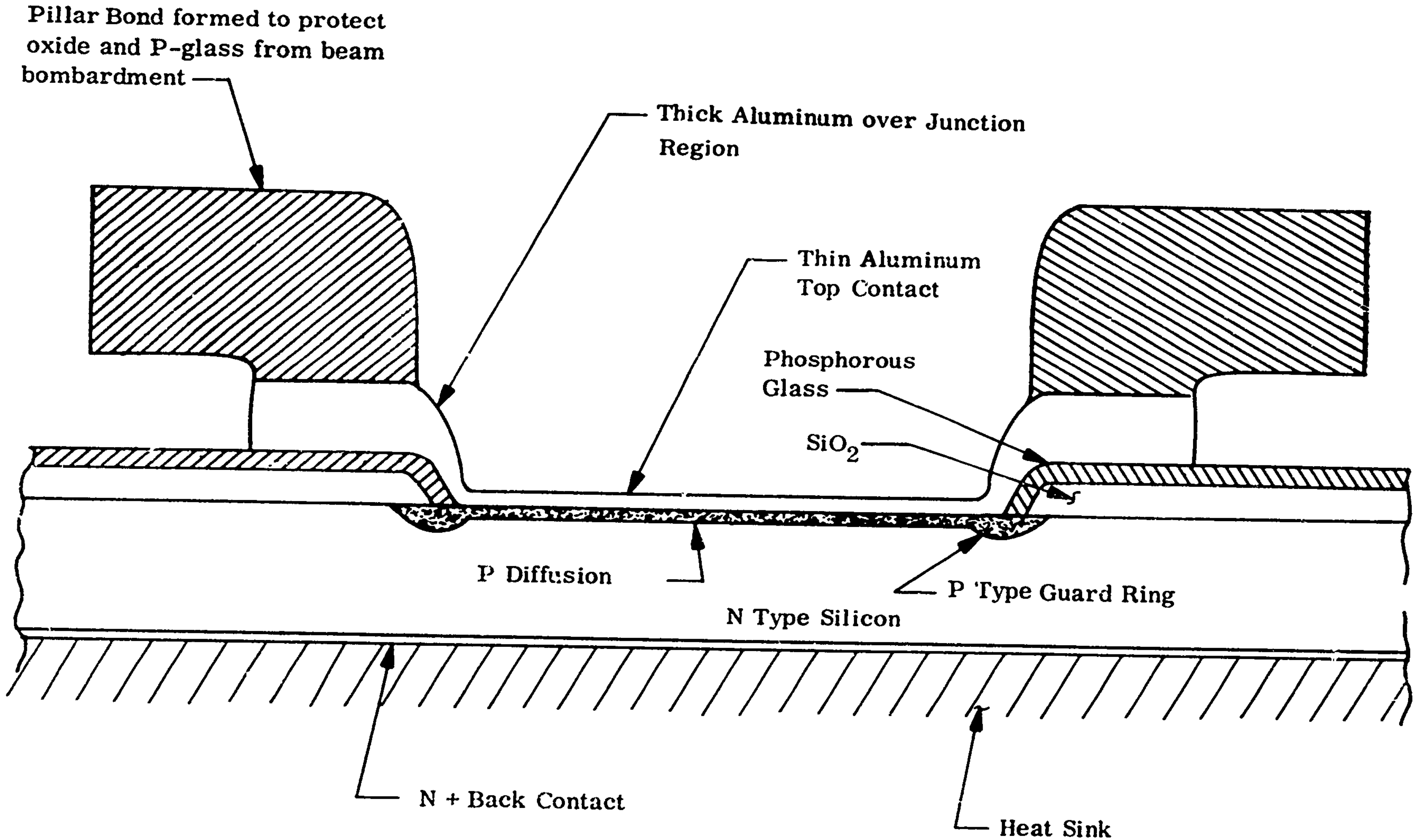


Fig. 3.4 – Radiation hardened diode using a pillar bond formed to protect the oxide and P-glass from beam bombardment.

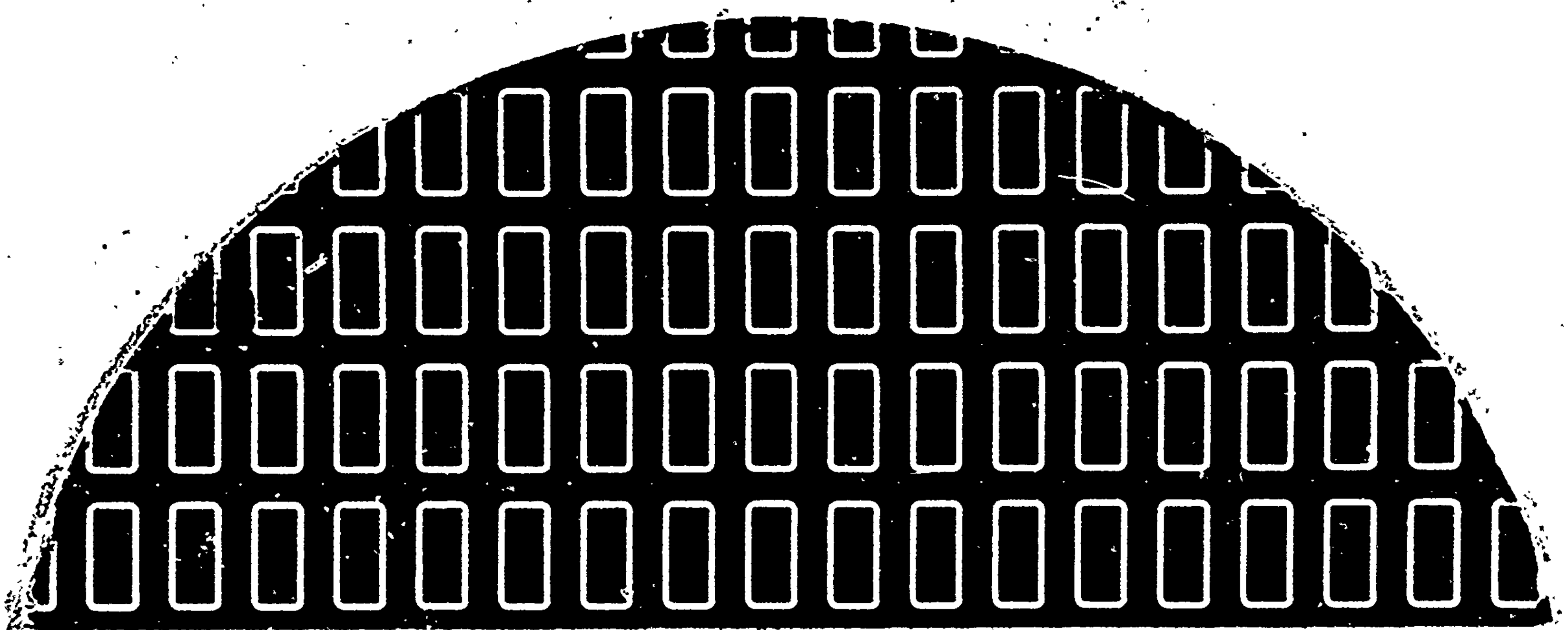


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Fig. 3.5 – Photograph of diodes fabricated with the integral beam shield. The lighter areas are the pillar bonded beams approximately 4 mils wide and approximately 1 mil above the wafer surface.

diode. The diode without the integral beam mask, is identical in every respect except for the actual mask itself. The diodes were tested first with 10 keV bombardment and 150 volts bias. The diode without the integral beam mask showed an increase in leakage current from less than 1 μA up to 50 μA over a period of approximately 20 minutes. This magnitude of increase in leakage current has also been observed in these diodes when tested in an EBS device. When an integral beam shield protected diode was tested, within experimental accuracy, the leakage current showed no increase. We estimate that the leakage current increase, if any, was less than 1 μA.

The electron beam voltage was then increased to 18 kV. At these higher beam voltages, the beam penetrates deeper into the passivating layer and the leakage current increases in diodes without the integral beam mask. However, no such increase occurred in the integral beam mask diodes.

We believe that this result is very significant to the development of a highly reliable radiation-resistant semiconductor target for EBS devices. Therefore, the integralbeam mask will be used in future devices. A fabrication run of these diodes is presently in process.

It should be noted that the diodes protected with the integral beam shield do not have significantly higher capacitance than unprotected diodes. The beam shield is designed in such a way that the voltage gradient within the silicon and in the oxide passivating layer is approximately the same as in unprotected diodes. Therefore, no additional stray capacitance has been introduced.

4.0 FABRICATION AND TESTING OF COMPLETE PULSE AMPLIFIERS

Fabrication and testing of three high current switch tubes was completed during this reporting period. In addition, the technology development of fabrication techniques continued. The tubes were processed through bakeout and cathode activation and one of the tubes was operated with an internal getter instead of a two liter appendage pump. The following sections will briefly describe the additional development of tube fabrication technology and test results on Tubes S/N 6, S/N 7, and S/N 8.

4.1 Fabrication Technology and Tube Processing

The objective for the high current pulse amplifier has been not only to meet the design goal of high current short pulse operation, but also to develop a completely processed tube suitable for use in future military systems. Therefore, considerable effort has been devoted to developing a tube design which would be compatible with state-of-the-art high vacuum technology.

The extremely high current capability expected of the EBS switch requires a large cathode and grid structure. This coupled with the seven mil cathode-to-grid spacing imposes rather stringent fabrication requirements. The grid and grid mounting ring have been made from photoetched molybdenum and porous tungsten respectively. This combination of materials compensates for the thermal expansion due to heat transfer from the cathode. The grid-to-grid ring braze is a very critical step in the tube fabrication. The grid must be brazed so that it does not distort over a very wide range of temperatures. During this reporting period, the brazing technique was refined. Following the braze each grid assembly is heat cycled in a vacuum bell jar so that any grid distortion can be visually noted. The grid structures made with the present technique do not show any distortion at cathode temperatures well in excess of the design operating temperatures.

An additional key step has been the inclusion of a getter within the tube envelope. In the first tube using a getter, the amount of getter material and the mounting position was not satisfactory and the getter configuration has been redesigned. During the next reporting period we expect to complete the getter development and deliver switch tubes without an appendage pump. Figure 4.1 is a photograph of a high current EBS switch after bakeout and pinch-off from the appendage pump.

4.2 Pulse Test Results

Three high current pulse amplifiers were fabricated during this reporting period; Tubes S/N 7, 8, and 9. Tube S/N 6 was fabricated previously. This section presents a summary of test results obtained from Tubes S/N 6, 7, and 8. Tube S/N 9 was lost due to a vacuum leak and test results were not obtained.

The testing was directed toward a detailed understanding of device operation, rather than achieving higher peak currents or faster risetimes. All tubes tested during this period contained two quarter section .35 cm^2 area targets, and all diodes had 37 μm depletion region thickness and 22 ohm-cm resistivity.

The EBS switch was tested both with the pulse applied to the grid or to the cathode. A schematic of the test circuit used to pulse the cathode is shown in Fig. 4.2. The cathode pulse circuit was developed because it provides better isolation of the RF input and output circuits, analogous to conventional grounded grid triode operation. Since the grid is held at RF ground, it effectively shields the input pulse from the output, target end of the tube. A comparison of test results showed no significant differences in output pulse shapes, thus either input circuit configuration is suitable. Further verification will be sought when full size targets are tested at higher current levels.

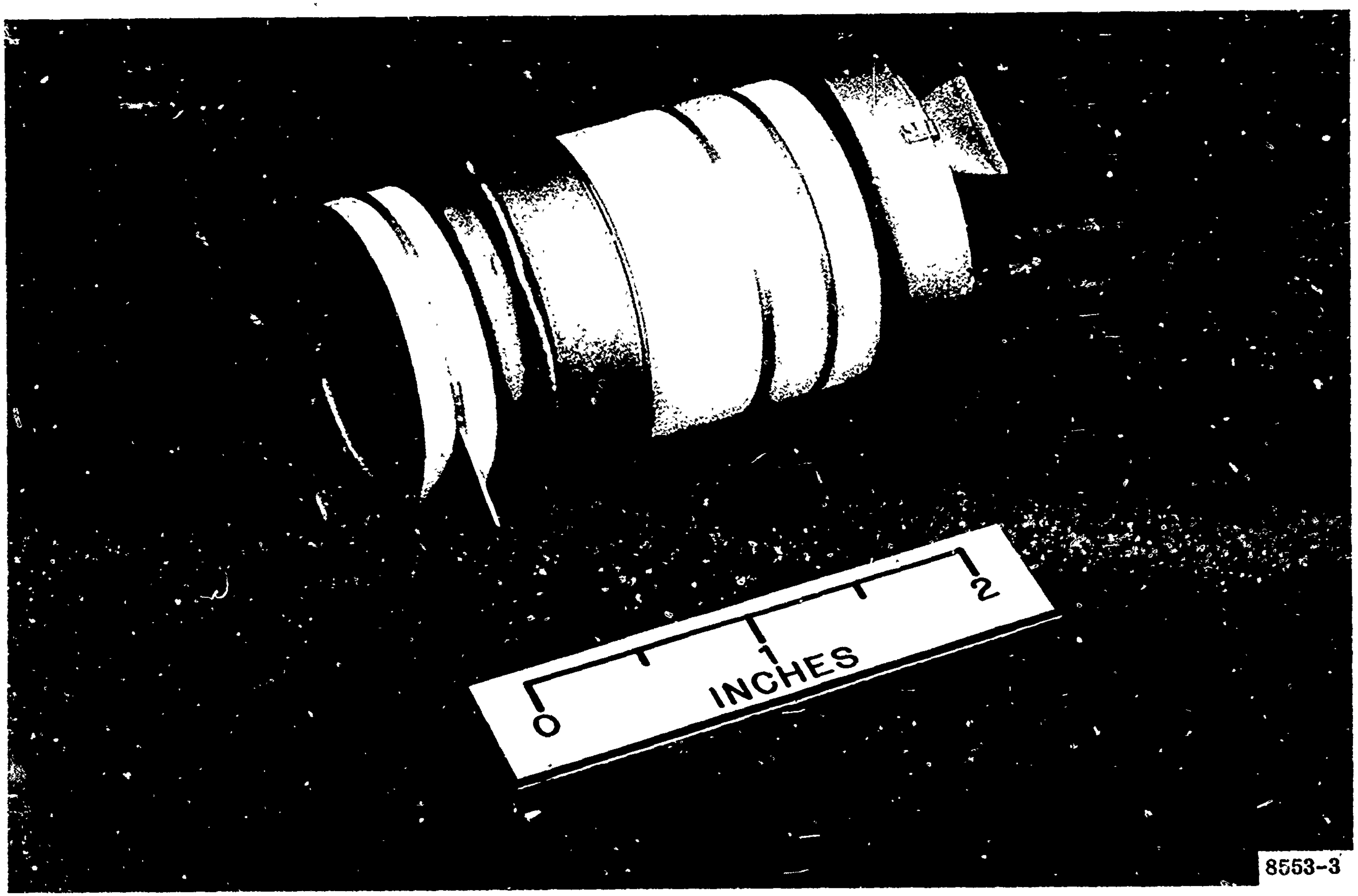


Fig. 4.1 - High current EBS switch after bakeout and pinch-off. The appendage pump has been replaced by a getter inside the tube

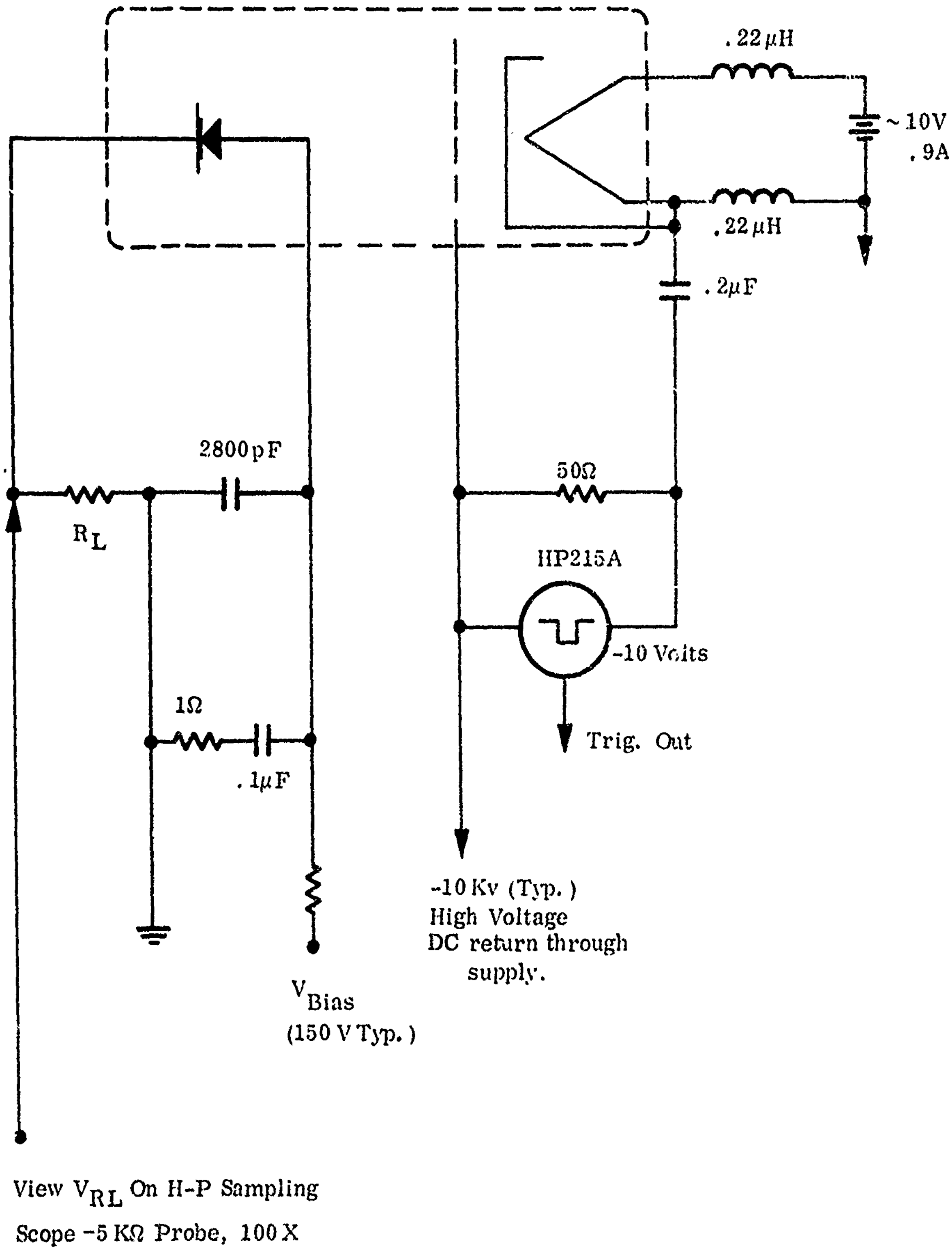
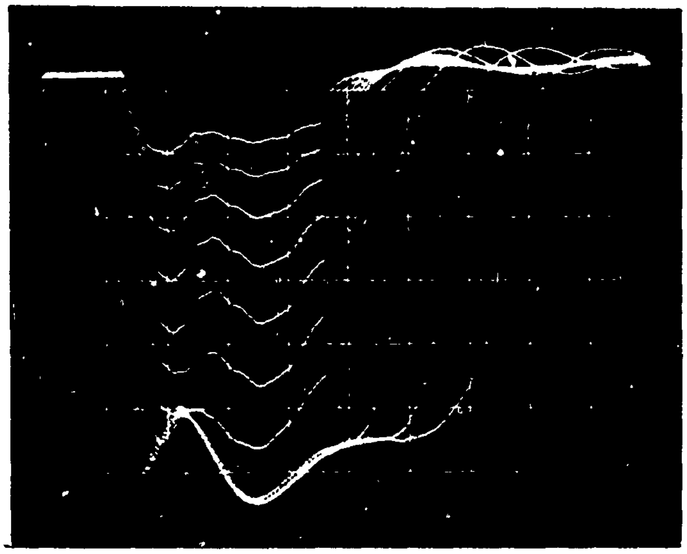


Fig. 4.2 - Schematic of test circuit used for cathode pulsing tube S/N 7. Operation with grid at RF ground provides optimum isolation of input and output circuits.

The testing program was also intended to verify the semiconductor diode design parameters and transconductance of the grid-cathode structure. Figure 4.3 and Fig. 4.4 show diode operation into 10 ohm and 5 ohm loads respectively. These test results are on tube number S/N 7 and are representative of the other tubes. The higher load impedances were selected so that diode saturation could be measured at lower beam currents. As can be seen from Fig. 4.3, with a 10 ohm load and 145 V diode bias the diode saturates at approximately 130 V. If the beam is increased beyond saturation, a pulse stretching occurs due to charge storage and collapse of the electric field in the diode. Fig. 4.3a shows the saturation characteristics as the input pulse is increased while Fig. 4.3b shows similar saturation characteristics as a function of beam voltage.

Figure 4.4 shows the results of this experiment repeated with the 5 ohm load on the output. Once again diode saturation is indicated by the pulse stretching. It is possible to saturate the diode both with the input RF pulse or by leaving the input pulse at a given setting and increasing the beam voltage. Fig. 4.4 shows that diode saturation in this case occurs at approximately 120 V. This lower output voltage is due to the higher current into the 5 ohm load which causes the electric field to collapse at a diode voltage of 25 V instead of 15 V. The experiment was also tried with 2.5 and 1 ohm load impedances. The result of the lower load impedances showed that 2 ohms is the lowest load impedance for which the diodes can be saturated with a 10 kV beam.

Finally, it should be noted that the output pulse at the higher current levels has considerable ringing, which may limit the device applications as a pulse amplifier. We have not yet been able to identify all of the effects which degrade the pulse shape. However, tests using a passive target indicate the problem is largely due to the input pulse coupling system. We expect to achieve significantly improved performance during the next reporting period.



Output pulse from tube S/N 7 with $R_L = 10\Omega$

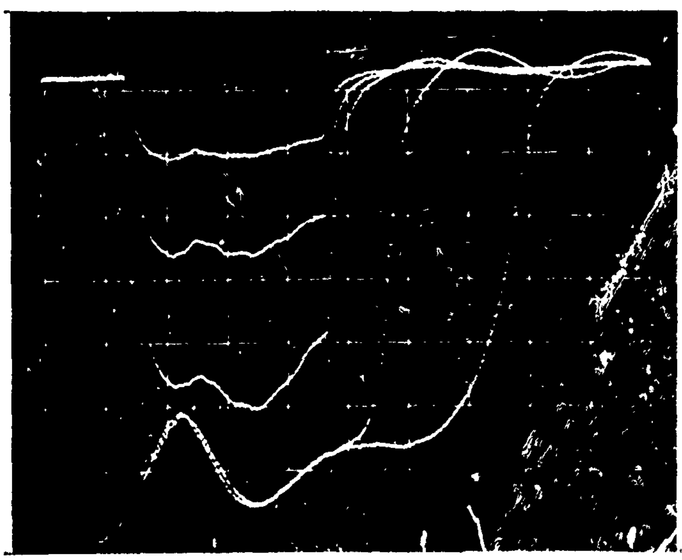
145 V Diode Bias

10 kV Beam

1 dB steps in grid pulse

2A/cm

20 nsec/div



Output pulse from tube S/N 7 with $R_L = 10\Omega$

145 V Diode Bias

6 kV Beam Voltage

7 kV Beam Voltage

8 kV Beam Voltage

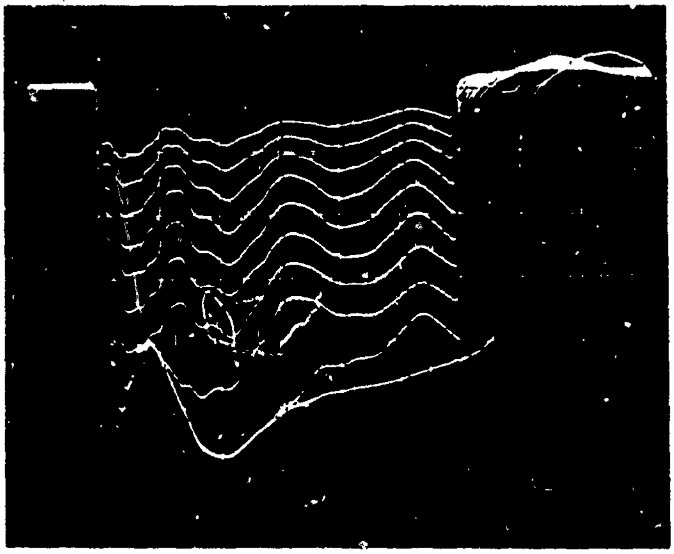
9 kV Beam Voltage

10 kV Beam Voltage

2A/cm

20 nsec/cm

Fig. 4.3 - Diode operating characteristics into 10 ohm load. Diode saturation occurs at about 130 volts output as predicted by a large signal computer analysis.



Output pulse from tube
S/N 7 with
$R_L = 5\Omega$

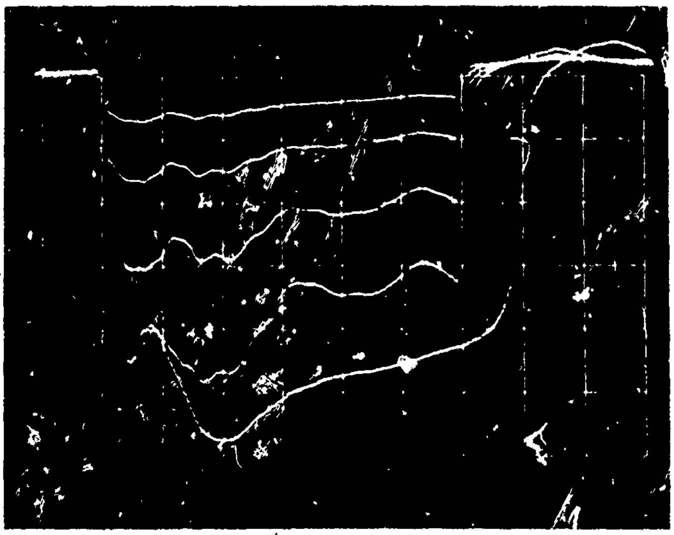
145 V Diode Bias

10.2 kV Beam

1 dB steps in grid pulse

4A/cm

20 nsec/cm



Output pulse from tube
S/N 7 with
$R_L = 5\Omega$

145 V Diode Bias

6.2 kV Beam Voltage

7.2 kV Beam Voltage

8.2 kV Beam Voltage

9.2 kV Beam Voltage

10.2 kV Beam Voltage

4A/cm

20 nsec/cm

Fig. 4.4 - Diode operating into 5 ohm load. Diode saturation is indicated by the pulse stretching and occurs at about 120 volts output.

4.3 Discussion of Results

Although the experiments described above did not result in the achievement of new performance levels, significant new information was gained which can be applied to the design of the engineering prototype EBS switch. The experiments were carried out concurrently with the development of semiconductor and vacuum fabrication technology so that information obtained can be incorporated into the final semiconductor and tube design. The experiments showed that with a small improvement in the grid-cathode structure device transconductance at a level sufficient to fully operate the high current switch can be obtained at a beam potential of 12 to 15 kV.

The semiconductor targets saturate at the expected output voltage levels. However, a minor design optimization may be necessary to provide full diode depletion at somewhat lower bias voltages.

The pulse shape distortion was identified primarily in the input circuit and we are presently investigating other configurations to reduce input pulse distortion.

In conclusion, we believe that with the information obtaining during this reporting period design modifications can be made which will result in a satisfactory engineering prototype pulse amplifier.

5.0 PROGRAM FOR THE NEXT INTERVAL

The device fabrication and testing will continue. Design refinements will be made as indicated by the work during this reporting period. The program emphasis will be on experiments to achieve design goal performance and to correlate the analysis to verify the amplifier design.

Details of the program for the next period are shown in Table I of this report. We expect to complete all of the proposed tasks shown in Table I. Additional projections of expected progress are described in the Report Summary Section.